Title: **Feasibility of Low Cost Fabrication of Lightweight, Protective Structures using Thermoplastic Matrix Composites**

Final Report

by

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13. ABSTRACT *(Maximum 200 Words)*
An investigation has been carried out into the low cost fabrication of lightweight thermoplastic composites for ballistic protection. Panels have been manufactured over a range of conditions using lightweight ballistic reinforcement, interleaved with polymer films. The ease of production is promising, and even at relatively low molding pressures and times the panels are well consolidated. Quasi-static penetrative tests were carried out using a Fragment Simulating Projectile (FSP) and have established correlation with other studies in terms of the mechanism of failure during penetration. Energy absorbance shows some relation to molding parameters although further testing would be required to draw any substantial conclusions. Cone formation and back-face deformation was also observed for S2-glass/LDPE panels and has been reported in the literature as being one of the major methods of energy absorption. Ballistic evaluation is still to be carried out on such panels, but following completion of the data set an appendix will be issued with results and discussion updated appropriately.

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1 Introduction

Fiber-reinforced composites have outstanding mechanical properties and over the last three decades have seen increased use in high performance applications such as ballistic protection. Synthetic textiles have been used for personal protective equipment (PPE) since World War II and the development of fibers such as aramid and gel spun HDPE has lead to a reduction in the weight and bulk of modern ballistic resistant vests and jackets. Combining these fibrous materials with a polymeric matrix allows production of laminates for use in applications such as helmet shells and vehicle armor where a rigid shape and/or load bearing capabilities are required.

An intrinsic problem with composite materials, however, is their limited ability to cope with localized impact and the ballistic performance is lower than that for fabric systems of comparable weight. The matrix material contains the fibers, preventing slippage but also limiting their ability to deform and reduces the dissipation of energy to a relatively small region. Many ballistic composites are therefore designed to absorb energy by delaminating upon high velocity impact. Delamination can, however, be caused accidentally by events such as the dropping of a tool onto a vehicle or as a result of rugged physical conditions in which soldiers are required to operate. For this reason efforts have been made to improve the damage tolerance of composite armor.

Toughened thermosetting resins such as Polyvinylbutyral + Phenol formaldehyde (PVB+PH) are currently used, however, thermoplastic polymers are inherently tough, generally lighter and more durable as well as having better chemical resistance to harsh environmental conditions. A further advantage is the ability to melt-process, which offers a significant reduction in costs for high volume production and also allows field repairs to be carried out.

Lightweight and economical thermoplastic composites may therefore replace existing armor systems in certain non-load bearing applications as well as allowing the production of affordable large structures such as lightweight tactical operations shelters and shelters for the High Mobility Multipurpose Wheeled Vehicle (HMMWV). There is also the possibility that this type of ballistic protection will enable the development of PPE for human extremities, forearms, wrists, and shins etc, which are currently unfeasible due to weight and cost limitations.

The aim of this project was therefore to investigate the low cost fabrication of lightweight thermoplastic composites for use as ballistic protection. The main objective was to produce a series of thin, lightweight panels using a range of thermoplastics under different processing conditions.

1.1 Ballistic Review

Numerous studies have taken place investigating the ballistic performance of various textile and composite armors. Energy absorption is highly complex and is facilitated by a number of different mechanisms that include tensile failure of fibers, elastic deformation, delamination, shear between layers and inertia of the material. The differences between fabric and composite construction as well as varying impact conditions means that no single model can be applied and there remains much debate about the extent to which the various mechanisms absorb energy.

1.1.1 Energy Absorbing Mechanisms

Morye et al [1] have studied gel-spun polyethylene, aramid and Nylon-66 fiber textiles and highlighted three main energy absorbing mechanisms. Energy is absorbed in tensile failure of fibers, and by elastic

deformation and inertia of the composite. Impact of fiber armor systems is shown to result in the formation of a cone on the back face caused by transverse wave that propagates from the point of impact. Primary yarns are strained to tensile failure while secondary yarns are deformed elastically due to the formation of the cone. Energy is also absorbed as a result of the kinetic energy of the moving portion of the target and this was found to be the dominant mechanism

Focht and Vinson [2] have also found that a conical shell forms in laminates during ballistic impact and that resistance to penetration is primarily due to membrane strain energy. They comment that if a matrix material is used that contributes little to the composites mechanical properties then the entire structure would behave in a similar way to a woven fabric.

Gellert et al [3] observed that the deformation process changes as the projectile proceeds through thick GRP panels. The first phase dominated by acceleration of target material, shearing, compression and crushing ahead of the projectile. Latter stages involve the stretching of fibers, dishing and delamination due to diminishing restraint to crack opening. For thin targets damage occurred in the second of these two distinct phases, with a cone of delamination opening towards the exit side. Transition in energy absorption was observed at a certain thickness for both GRP and Kevlar composites, and that this change leads to a bi-linear relationship of ballistic limit against target thickness, where greater energy is absorbed by thick targets under going both phases of deformation. Gupta (cited by Wu and Chang [4]), however, found a linear relationship between the projectile energy loss and the target thickness.

This change in mechanism through thickness is supported by Langlie and Cheng, (cited by Iremonger [5]) who identified transverse shear failure in the front layer, tensile failure in middle layers and delamination towards the rear of the target.

Further study by Gellert et al used high-speed cine photography to examine thin targets produced from a range of fabric and composite types [6]. Fabric systems were shown to perform better than composites on the basis of areal density. It is suggested that a higher proportion of energy is absorbed as tensile strain energy rather than kinetic energy. Energy absorbed by delamination in composite systems was calculated from the fracture toughness G_1. Gellert et al also found evidence to support Prosser's conclusions that a cutting/shearing mechanism was predominant during penetration of Polyamide textiles targets by FSP [7].

There is clearly a combination of different mechanisms taking place during ballistic penetration and the extent to which each one facilitates energy absorption is dependent on a number of factors. It is apparent from the literature cited above that the most prominent difference in energy absorption is between dry fabric armor and composite panels. Other important factors appear to include projectile geometry and fiber type/weave style.

1.1.2 Factors Affecting Energy Absorption

One of the most significant influences on energy absorption is the geometry/nose shape of the projectile. The main threat in these sorts of battlefield applications is from fragments cause by exploding munitions such as bombs, shells and grenades. For this reason assessment of armor systems in both industry and academic study is often carried out using a fragment-simulating projectile (FSP). The most commonly used FSP is a chisel-nosed steel cylinder with unchamferred 90° and oblique 55° edges. Projectile of this type can vary in caliber and mass and are designed to represent a variety of different size and potentially sharp fragments.

Prosser's investigation [7] highlights the effect of projectile nose geometry as a factor in causing a cutting/shearing failure of the fibers. Gellert et al [3] found that for thick GRP targets, pointed projectiles are more effective. For thin targets, however, he found that energy absorbed was largely independent of

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different projectile nose shapes. They also found that the response of thin targets appeared to be independent of materials with both GRP and Kevlar targets responding in the same way.

Cunniff [8] has investigated the system effects of different woven fabric construction. Loosely woven fabrics and those with low yarn-to-yarn friction experience slippage around the projectile as it penetrates, resulting in low energy absorption. From a consideration of force balance about the projectile it is concluded that the impulse doing work on the projectile is due only to the component of tension in the principal yarns. From this conjecture the implication is that ballistic reinforcement should be tightly woven with a high count of ends/cm. Balanced weave fabric systems are known to provide superior ballistic performance. Unbalanced weaves experience a transverse wave that is more pronounced in one direction than another and therefore less of the material is under strain.

Prosser's investigation of polyamide textile armor has shown the effect of projectile geometry. It is shown that that penetration will occur in the easiest manor possible. Since the shear strength of Polyamide fiber is half than that of the tensile strength, then it is no surprise that failure occurs by cutting/shearing, particularly at the right-angle quadrant of the FSP. In order to improve ballistic protection against shrapnel, fibers with a better balance of tensile and shear strength should be used.

Gellert et al [6] found that the overall mechanism of penetration in aramid panels was similar to that of polyamide laminates. A similar change in failure mechanisms around the periphery of FSP was observed. There does, however, appear to be a difference in mechanisms of failure of individual fibers. Aramid fiber ends fibrillated, i.e. split, when broken which is a well known characteristic and contributes to their high energy absorbing capability.

Goldsmith et al, and Cantwell and Morton, conclude that for glass and carbon reinforced laminates negligible energy is absorbed in tensile failure of the fibers. Zhu et al, and Zee and Hseih, however, acknowledge the importance of this mechanism for more extensible thermoplastic fibers (cited by Morye et al [1]).

1.2   Thermoplastics Matrix Composites (TMCs)

Although thermoplastics have a number of advantages over thermosetting resins, one major disadvantage is the high viscosity of the polymer melt. As a result high pressures and long processing times are sometimes necessary for full consolidation of the reinforcement. The tooling required to achieve this is expensive and lengthy fabrication processes are not ideal for low cost, high volume production. Smith et al [9] have also found that high pressure can lead to fiber damage, particularly when using woven fabrics where tows cross one another. In contrast to normal consolidation requirements, Iremonger and Went [5] observed that lower pressures for thin EVA matrix helmets actually gave improved ballistic performance as the fibers form a more open structure and are more able to deform.

Rather than using high pressure, better consolidation can alternatively be achieved by using high temperatures. Viscosity reduces with increasing temperature and the polymer melt can flow into the reinforcement more easily. High temperature can, however, lead to oxidization and thermal degradation, and this in turn raises considerations about the length of molding time. Special tooling and ancillaries may also be required for high performance thermoplastics, and along with greater energy consumption this again leads to an increase in processing costs. High temperature may not, however, be necessary. A study by Song [10] has found that amorphous polymer composites actually appear to have better ballistic properties when produced below their full flow temperatures.

A material solution to low melt viscosity is to reduce the distance over which the polymer melt must flow. An increasing number of products are supplied in a form where the polymer is contained within or close to fiber tows. Mixing thermoplastic fibers with the reinforcement fibers is known as commingling

and gives flexible tows that can be easily woven and draped to produce complex shapes. Powder and solvent impregnation can also be carried out, although these tend to give rigid tows with a defined elliptical shape. This type of tow is harder to weave and limits the types of fabric construction available.

Another more recent material solution is the development of reactive thermoplastics. These are available as a low viscosity resin and can be processed using similar methods to resin transfer molding (RTM) of thermosets.

These aspects are normally intended to improve panel consolidation, however, one should bear in mind that this may not necessarily be desirable. Improved ballistic performance is observed when using all fabric armor or composites with a less stiff matrix [Iremonger]. In these cases the more flexible interfaces between the plies of fabric causes a reduction in stress wave propagation through the thickness of the material. The plies are also better able to slide over one another allowing greater deformation and dissipation of energy.

Reinforcement impregnation and low melt viscosity are not, however, the only consideration when molding thermoplastic composites. Many common polymers have a semi-crystalline structure, the degree of which is significantly influenced by the cooling rate following melt processing. Song [10] found that the presence of the reinforcement did not influence the formation of crystals, but more significantly that cooling rate and crystal perfection had minimal affect on the ballistic properties.

1.2.1 Processing Methods

Depending on the application and the types of materials being used, thermoplastic composites can be produced in a variety of ways. Considering the factors detailed above, continuous fiber reinforced panels of the type under investigation may be produced in one of four ways:

Compression molding

The material is heated above the T_m of the polymer and compressed under pressure for an appropriate time in order to consolidate the panel. This method can be used for nearly all forms of thermoplastic composites from pre-impregnated to constituent materials. Heating can either be carried out in an Infra Red (IR) oven prior to transfer to the press, or by contact heating within the press itself. IR oven heating followed by compression reduces the time in the press, but transfer time is critical, and the polymer begins to solidify as soon as it enters the press. Heating the stack in the press requires higher temperature tooling and the associated cost increase. For quick turn-around the stack must also be placed between an additional set of removable tools.

Vacuum forming

Generally the material is placed against a one sided tool and the vacuum bag and ancillaries placed above the stack. The vacuum is then applied and the whole assembly placed in an IR oven for heating to the required temperature. As the polymer melts a combination of atmospheric pressure and the vacuum facilitate consolidation. This process is slower than compression molding, however, the vacuum means that void content is generally lower and also the absence of air reduces the effects of oxidative degradation. Consolidation by the use of atmospheric pressure and vacuum also means that this process does not require any expensive high-pressure tooling. The common materials for vacuum bagging are generally intended for low temperatures use with thermosets and polymers such as PP. When molding with high melt temperature thermoplastics, high and ultra high temperature vacuum bagging materials are usually required these being very expensive. A low cost alternative may be to use materials that are

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not specifically intended for this process. The use of thick Al foil and fine woven metal mesh, or wire wool as a breather felt may be possible.

Autoclaving

This process is similar to vacuum molding although it takes place within a pressurized chamber. The material is placed between two flexible membranes and a vacuum applied. The chamber is then heated up to the required melt temperature and pressure applied to the outside of the membrane to consolidate the material. The pressure on one side of the stack is then increased and it is forced down onto a shaped tool where it is held under pressure while the temperature is reduced to below the melting point.

Reaction Injection Molding

Using reactive thermoplastic resin systems, composite panels can be produced using a similar process to resin transfer molding (RTM). This process is still in the early stages of development and materials for this type of process are mainly limited to polyamides.

2 Experimental Method

2.1 Materials

2.1.1 Pre-impregnated TMCs

Commingled and pre-impregnated fabrics were initially considered as the easiest and most cost effective materials to process. The range of polymer/reinforcement combinations in this class of material is becoming more and more diverse, however, fabric construction is still fairly limited to standard weights and predominantly 2x2 basket weave styles. The importance of fabric construction for this type of application has already been discussed, and although these materials offer advantages in terms of handling and processability, they are not ideally suited for ballistic protection. A limited number of pre-impregnated materials have, however, been included in the investigation in order to provide comparative data.

Applied Fiber Systems, a subsidiary of Hexcel, supplied three ready-molded panels with combinations of E-glass/Polyamide 6, S2-glass/PEEK and S2-glass/PEI. Material construction is a 2x2 twill weave fabrics made from powder impregnated Towflex® yarns. Again the weave style is not specifically suited to this type of application and although S2-glass reinforcement has been used this is not of a ballistic grade.

Twintex is a commingled E-glass/PP fabric produced by Vetrotex-St. Gobain. It is available in two common styles, 2x2 and 4x1 twill weave. Balanced fabrics give better ballistic performance and therefore the 2x2 style material will be used to produce large panels for ballistic and other testing. This material is also available in a pre-consolidated sheet form that can be easier to handle for certain applications. Both forms will be molded.

2.1.2 Reinforcement

E-glass, S2-Glass, aramid, polyamide and gel-spun, high-density polyethylene (HDPE - Dyneema® and Spectra®) are common reinforcement materials used in ballistic applications. Carbon has been used in

some structural ballistic applications, although it has relatively low impact energy absorption and is prohibitively expensive for this study into low cost processing. Gel-spun HDPE offers excellent ballistic resistance and low density but suffers from similar cost penalties to carbon. In addition, the complication of processing thermoplastic reinforcement with thermoplastic matrix materials discounts HDPE along with polyamide.

As well as fiber type, investigations have highlighted the performance of different weave style under ballistic impact [7, 8]. The literature suggests that balanced plain weave fabrics between 200 and 300 gm^{-2} are the most effective against small arms and fragment threats. Since the yarn parameters (yarn count and ends/cm) may also play a significant role, fabric parameters were required to be as similar as possible for comparison in terms of both ballistic performance and processing.

For the purpose of this investigation therefore three types of reinforcement materials have been considered. $210gm^{-2}$ plain weave E-glass was intended as a low cost, baseline material, to act as a vehicle for process prove-out, while $200gm^{-2}$ plain weave Kevlar® and ballistic grade S2-glass are to be used to produce panels for ballistic testing.

Lightweight fabrics of this type are also thin in comparison to many other reinforcement types. The distance over which the polymer melt is required to flow is therefore relatively low, making the manufacture of composites using these materials more feasible.

2.1.3 Polymers

Five matrix materials have been investigated and include commodity thermoplastics: polypropylene (PP) and low-density polyethylene (LDPE), engineering polymers: PA6 and thermoplastic polyester (PET), and polycarbonate (PC) as a high performance, high impact comparison. Each of these materials was procured in film grades although a variation in thickness between $50\mu m$ (PA6) and $250\mu m$ (PC) was forced due to availability. Polysulfone (PS) and Polyamide (PA12) were also obtained in granule form with the view to casting into a film or grinding to a powder. This proved difficult and it was decided to concentrate on the commercially available polymer films and processing by compression molding of an interleaved stack.

2.2 Thermoplastic Composite Production

Although investigation of wide range of materials and fabrication methods was intended, the basis for this study has concentrated mainly on compression molding. This is considered to by the most appropriate and cost effective way of producing thermoplastic composite panels as a ballistic specific reinforcement can be easily combined with commercially available polymer films.

The surface treatment on the ballistic S2-glass has, however, proved to be highly heat sensitive and degradation occurs at temperatures of around 230°C. This is below the T_m of three out of the five polymers under investigation, and production of these panels is not currently possible. Contact has been made with the materials supplier and the nature of the surface treatment has been determined as a silane based coupling agent designed for epoxy resin systems. It also contains lubricants and processing aids that are the most likely cause of the problem. These are water-soluble and it may be possible to remove them using a jig dying process to pass the fabric through hot water.

In the mean time small panels have been produced using E-glass over a range of conditions and S2-glass for low T_m polymers. The results from quasi-static and observations are presented in this report and large panel production will be based on these results.

2.2.1 Small Panel Production

110x110mm composite laminates were made using plain-woven E-glass fabric impregnated by a film stacking method with five different thermoplastic polymers. A limited number of S2-glass panels were also produced, but when molded at temperatures above 230°C the fabric began to discolor and burn. This has been attributed to the low thermal stability of the surface treatment on the glass. Because of the low cost emphasis, test samples were molded under a relatively low pressure of 10bar and short processing times ranging between 1-5mins. Four temperatures were used for each polymer to cover the range of suggested processing conditions.

The laminates were assembled so that the external face of each pile finished with a layer of polymer film. The stack was then placed between two 110x110x5mm polished Al plates wiped with Ciba QZ13 high temperature mould release. A tray made from folded 1.5mm thick Al was used to prevent the film stack being squeezed from the Al plates during molding and to contain any polymer that was squeezed from the film stack. The assembled stack, Al plates and tray were then placed between two electrically heated platens mounted in a Hounsfield Universal Testing Machine. The top platen was then lowered and a preload of between 2-3kN (equivalent to approximately 2bar) applied during the initial stages of heating. Once at the required temperature the compression creep test facility of the machine was started giving a constant force of 13.2kN (equivalent to 10bar) for the duration of the molding time. At the required time the stack, Al plates and tray were removed and placed between two 19mm thick Al blocks. These blocks were to act as heat sinks and air was blown over them using a household fan to increase the cooling rate. Low cost and high volume production necessitates short processing times and since it has been shown that it has minimal affect [10], the use of a high cooling rate is advantageous. Method of cooling was kept constant throughout each set of panel production although the actual rate of cooling will differ depending on the materials and temperature at which they have been processed. Platens were monitored during heating and a twisted thermocouple was placed in the middle of the stack at one corner to record temperature throughout the whole process.

Upon cooling to a manageable temperature, approximately 60°C, the finished laminates were removed and prepared for testing. The visual appearance of the panel was noted and records kept for each set of panels.

2.2.2 Large Panel Production – continuing work

A limited number of large panels have been produced to date. Initial molding was carried out at the beginning of the project, but was stopped in favor of small panel production in order to reduce the amount of materials being used. Based on the results from these small panels, production will be resumed in order to produce the necessary large panels for ballistic testing.

Conditions used are as similar as possible to those used for small panel production. The stack is laid up using 650x650mm sections of fabric and 600x600mm of film and placed between two 700x700x5mm polished Al plates coated with QZ13 high temperature release agent. Again a twisted thermocouple is used to monitor temperature, and in addition a section of released Al foil is also placed in the middle of the stack at the top right corner. This foil prevents bonding and is designed to simulate a crack in order to test the fracture toughness of the material. The assembly is then placed in the Daniels press, which is heated to 15-20°C above the required temperature. The tool is closed and its own weight provides the pre-load while the stack reaches temperature. Platen temperatures were monitored and then reset to the required temperature at the appropriate time. As the center of the stack reaches temperature, a pressure of 10bar is applied for the duration of molding. Upon removal the stack is still above its melt temperature and contained within the Al plates. The assembly is then sandwiched between 19mm Al blocks and air blown across it using two household fans. The blocks of varying size were arranged evenly over the two surfaces and act as a heat sink to increase the cooling rate. In other similar

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production methods the panel would be removed and placed in a cold press to aid consolidation and prevent warping. The facilities are not available to do this, but although some warping of the panels has occurred, it is not excessive.

Upon cooling panel was removed from the Al plates. The useable section of the panel is approximately 600x600mm in size and from this area a number of test samples will be. A panel 12x12" is to undergo ballistic testing at ARL, a further 2/3 of the panel is to be used for quasi-static and drop tower testing while the remaining area will be used for mechanical and investigative testing.

Early panels produced in this way have included E-glass/LDPE, E-glass/PP, S2/LDPE and S2-glass/PP and were molded at a higher pressure of 37bar. Recent panels have also been produced using commingled Twintex in both fabric and pre-consolidated sheet form. Twintex material is of a heavier areal density and in order to get panels of a comparative weight and thickness 8 layers of material were used for each panel.

## 2.2.3 Testing

Quasi-Static Testing

An 80x80mm sample is used for quasi-static penetrative testing, based on the experiments done by Wang and Chou [11]. The sample was positioned over a hollow cylinder of diameter 50mm and clamped in place using four bolt tightened with a torque wrench to 20lbf.in. The clamping force was applied because the samples are thin and in some cases flexible. Without the clamping there is a possibility that the samples would simply deform and be pushed into the cylinder. The clamping force also simulates to some extent the constraint on the fibers that would occur within a larger panel. The specimens were then penetrated at a rate of 5mm min^{-1} using a 5.56mm (0.22 caliber) fabricated FSP.

3 Results and Discussion

Due to the problems and delays in molding large panels for ballistic the results presented here concentrate on quasi-static penetrative testing and observations made during the molding of small panels in the Hounsfield Test Machine. Once large panels have been produced and additional testing carried out an appendix will be issued containing the complete data set and discussions based on the analysis of this data.

3.1.1 Quasi-Static Penetration

Small panels were molded using E-glass reinforcement interleaved with film form of each of the five polymers under investigation. Table A.1 to A.5 (see appendix) give the molding parameters for these panels and figures 3.1 to 3.5 show the Normalized Energy Absorbed against Molding Time for each set of polymers. The normalized energy is the energy calculated from the area under the Force/Displacement graph divided by the areal density of the panels (g cm^{-2}). This was done because in some cases excess polymer was squeezed out and the resulting samples had reduced mass compared to others molded at lower temperatures and/or for shorter times.

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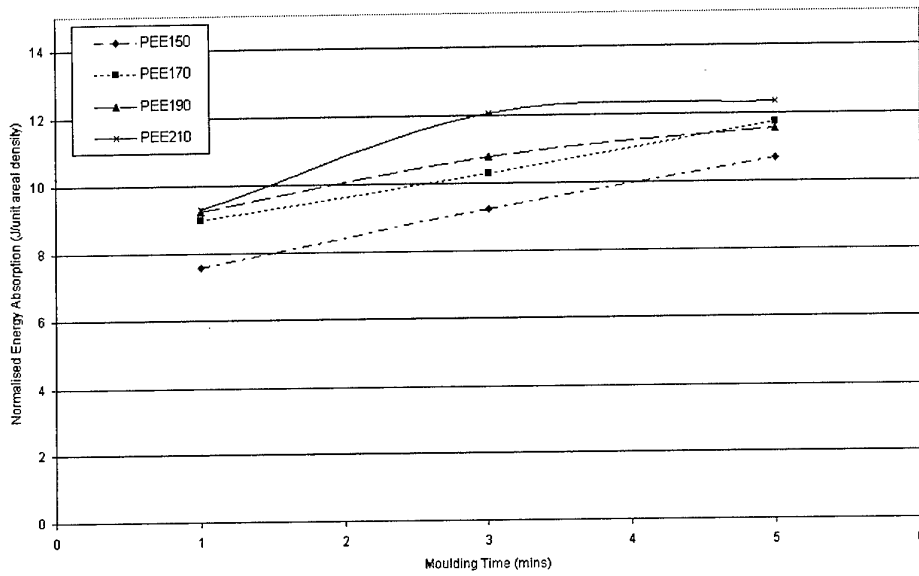
Figure 3.1 Normalized Energy Absorbed against Molding Time for LDPE/E-glass under Quasi-static Penetration by 5.56mm FSP
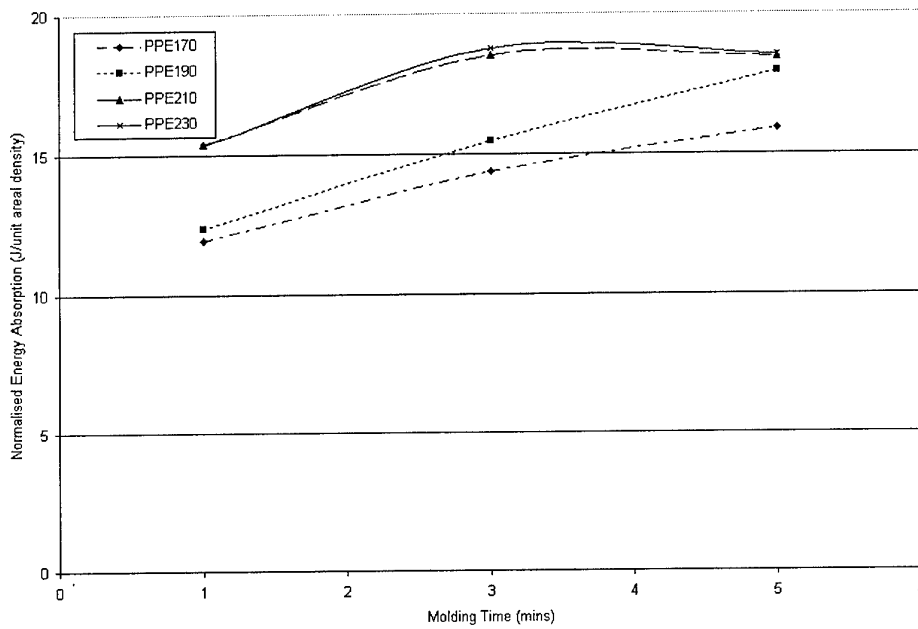
Figure 3.2 Normalized Energy Absorbed against Molding Time for PP/E-glass under Quasi-static Penetration by 5.56mm FSP
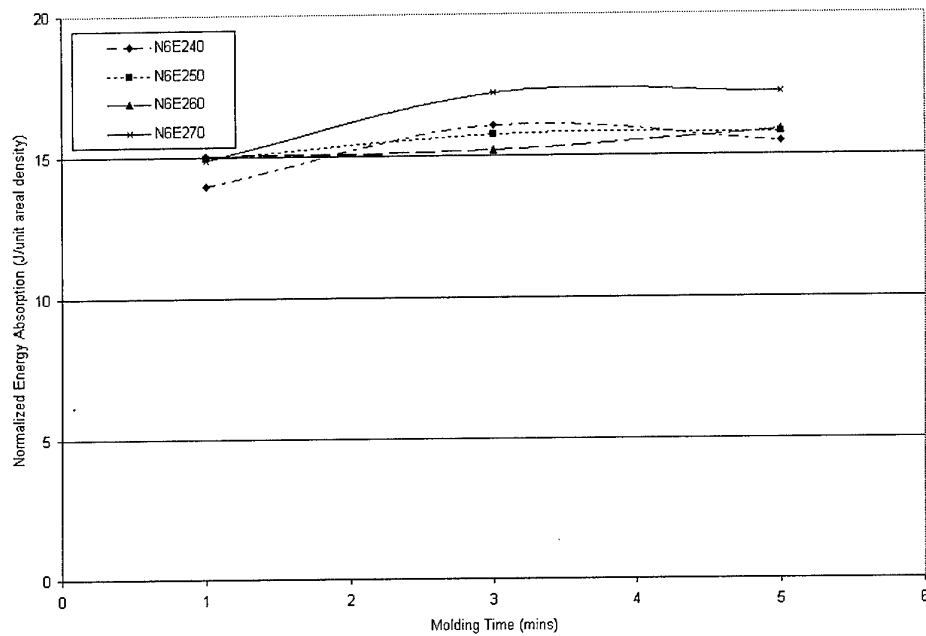
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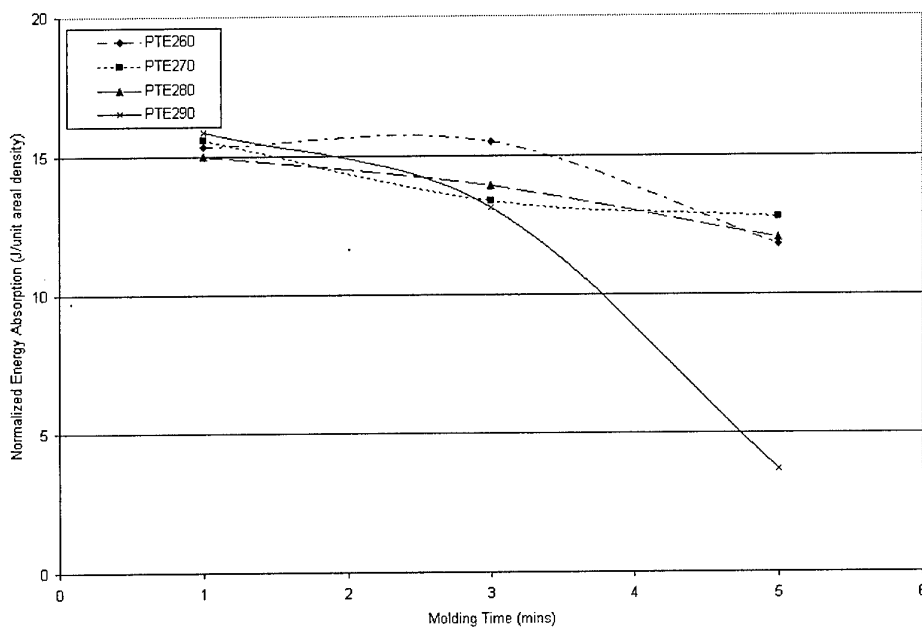
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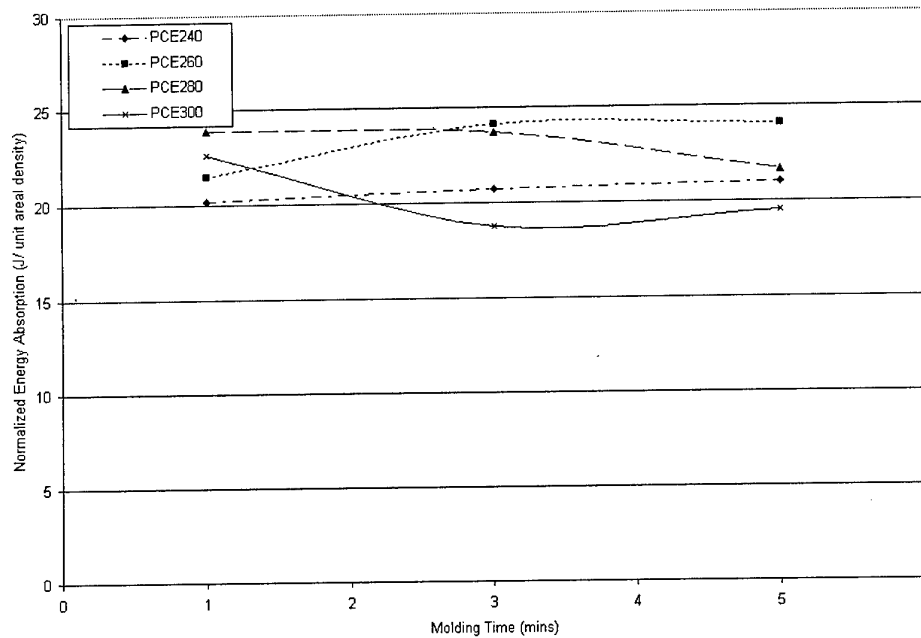
Figure 3.5 Normalized Energy Absorbed against Molding Time for PC/E-glass under Quasi-static Penetration by 5.56mm FSP

Some small panels were also molded using S2-glass reinforcement, however, the polymers used were limited to LDPE and PP due to the thermal degradation observed with the other polymers. This has been attributed to the low thermal stability of the surface treatment used on the ballistic grade of S2-glass. Tables A.6, A.7 and A.8 give parameters and test data for the panels molded with S2-glass along with information for the pre-impregnated Towflex® panels supplied by Applied Fiber Systems that have been included as a comparison. Figure 3.6 shows the Normalized energy absorbed for these panels.
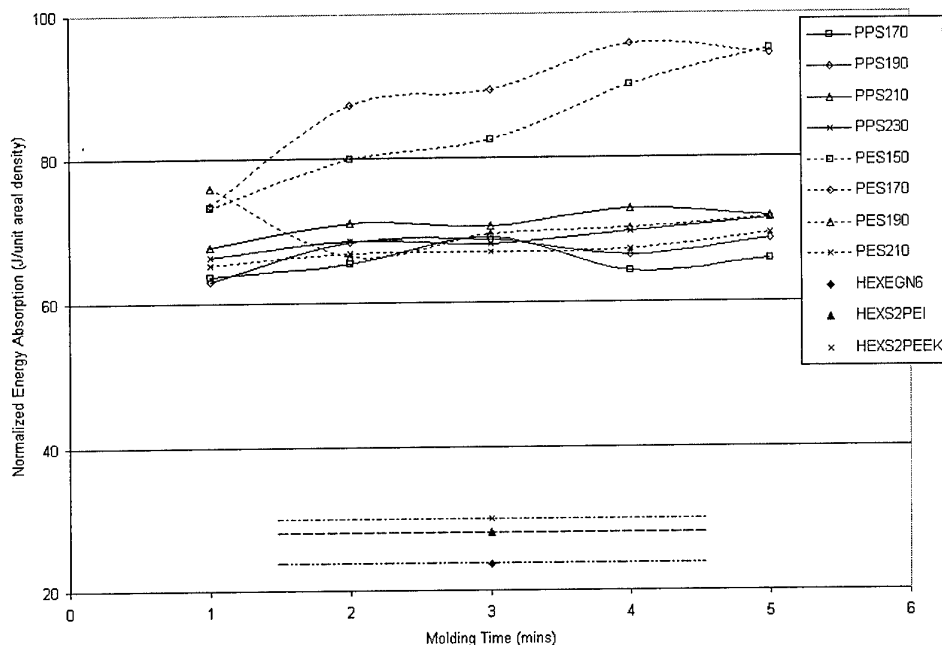
Figure 3.6 Normalized Energy Absorbed against Molding Time for LDPE/S2glass, Polypropylene/S2-glass and Towflex® panels under Quasi-static Penetration by 5.56mm FSP

The majority of results above show low energy absorption and are a reflection of the material properties of the E-glass reinforcement. It is in fact likely that for these samples resistance to penetration is primarily a function of the matrix material rather than through any major energy absorbing by tensile failure of the fibers. This is a potentially useful occurrence as it highlights the influence of the matrix material on energy absorption when it is not dominated by the reinforcement. It may, however, also be misleading when comparing materials to be used for panels produced with more typical ballistic reinforcements.

In this case energy absorption for PP/E-glass panels is consistently higher than for LDPE/E-glass, but the opposite trend is apparent for the same materials when using S2-glass reinforcement. This is interesting as LDPE has lower mechanical properties than PP and is considerably more flexible. These results therefore show some support for the theory that when a matrix material has a small contribution to the composite mechanical properties, then the structure will behave more like a woven fabric in the way energy is absorbed, Focht and Vinson [2].

The difference between reinforcements is also apparent from visual observation of the penetrated samples. The majority of E-glass panels exhibit a very small area of damage and tensile failure of the fibers occurs with little or no deformation of the rear surface. Even so it is still possible with some panels so see the difference in fiber failure mechanisms around the periphery of the FSP and in some cases a shear plug of material has been forced out.

The S2-glass panels are visually quite different and there is back face deformation, particularly apparent with the LDPE/S2-glass samples, showing evidence of the sort of cone formation usually associated with the transverse wave propagation in dry fabric armors Morye et al [1] and Cunniff [8]. Again cutting/shearing can be seen at the 90° edges while fibers have been strained to failure over the 55°

oblique surfaces of the FSP. This observation disagrees slightly with Iremonger and Went [5] who found that during penetration of Nylon 6,6/EVA laminate by an FSP, the mechanism changes with the reduction in energy of the projectile. Fibers that were being cut/sheared at the 90° face are instead bent and extended thus failing in tension. It is apparent from this testing that even under quasi-static conditions a cutting/shearing mechanism may still be occurring.

Samples from the pre-impregnated Towflex® panels were also tested and these are shown on graph as comparative data. All three panels showed considerably less energy absorption when compared to The LDPE and PP samples. PEEK and PEI are high performance polymers and again the fact that energy absorption was higher for the more flexible matrix materials shows the influence caused by the mechanism of failure.

3.1.2 Effect of Molding Parameters

Time/Temperature

Four temperatures were used to mould each of the different polymers and were intended to investigate the effect on energy absorption over the range of standard processing conditions from just above the T_m in some cases up to full flow temperature. Because of the focus on low cost production, molding time was kept intentionally short. Pre-impregnated materials such as Twintex can be processed for structural applications in a very short time, and in this case the low thickness of the reinforcement and possible desire for less than full consolidation were both considered. Molding time was therefore limited to a maximum of 5 mins and the majority of small panel production took place at time under pressure of 1, 3 and 5mins.

Results are not sufficient to make full conclusions, but there is some trend in terms of energy absorbed against time and temperature. E-glass with LDPE, PP and Polyamide 6, show and increase in energy absorption with higher molding temperature. The situation is less clear for PET and PC, although the highest temperatures in each of these cases (290°C and 300°C respectively) gave the lowest energy absorptions when molded for 3 and 5 mins. This is supported by Song [10], who found that for Kevlar/PC and Kevlar/PS composites the effect of processing temperature was significant. Samples manufactured at a high processing temperature around the manufacturer's full flow temperature (300°C for PC), were very brittle and failure was localized resulting in low ballistic limits. Samples molded at lower than full flow temperature exhibit less stiffness and better adhesion. Upon ballistic impact these samples show significant fiber motion accompanied by delamination of the composite. Ductile behavior along with good adhesion was found to contribute to high ballistic limits.

It was noticed that these two materials appeared to have a lower melt viscosity than the other polymers and this may contribute to the lower energy absorptions. When molded at higher temperatures for 5, and in some cases 3 mins, the excess molten polymer was squeezed out at the edge of the Al plates. This did occur to some extent with LDPE, PP and Polyamide 6, however, it was much less noticeable and did not result in a large change in mass.

There was also a noticeable difference in visual appearance of the PET and PC panels over the range of temperatures although as one would expect this was also related to the molding time. PET panels molded for 5mins at 270, 280 and 290°C all showed evidence of surface pitting where the polymer has flowed into the fibers and left voids at the surface. PC panels molded for 3 and 5mins at 260, 280 and 300°C all showed a translucent area at the center of the sample where full wet-out of the fibers is taking place. This size of this area increased with time and temperature.

The other polymers showed a little evidence of thermal degradation, particularly around the edges, as time and temperature increased, however, there was no major change in appearance.

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Pressure

Early moldings in the Daniels Press were carried out at a pressure of 37bar, however, Smith et al [9] found that high pressures can cause damage to woven reinforcement as the fibers are crushed. This was evident as sections from the panels molded with E-glass could be easily torn apart by hand. Again this may be due to the poor properties of this particular fabric, but it was decided to mould at a relatively low compression of 10bar not only to prevent fiber damage, but because of the associated reduction in processing costs. The low thickness of the reinforcement has meant that panels produced are well enough consolidated that it is not deemed necessary to increase the molding pressure above this level.

4 Conclusions

Much of the quasi-static testing has been carried out using E-glass reinforced panels and the low energy absorption is a reflection of the tensile and shear properties of this material. For this reason the PC panels exhibit the highest energy absorption in this case, as the polymer itself is very tough and has high impact resistance. In limited testing using S2-glass and LDPE and PP, however, much larger energy absorption occurred as well as a reversal in the trends from the E-glass panels.

Panels made with LDPE had much larger deformation of the rear surface and the flexibility of the matrix material allowed cone formation, and resultant straining of the fibers to tensile failure. Deformation also occurred with the PP/S2-glass panels, however, the higher rigidity of the matrix material limited this to some extent and the resulting energy absorbance was lower.

Although the E-glass reinforced panels gave relatively low energy absorbance they have been useful as a prove out material and shown that this type of interleaving fabrication is a realistic possibility for the production of thermoplastic panels. The lightweight and low thickness of the reinforcement means that even high viscosity polymer melts are able to impregnate and consolidate well. Fiber bundles themselves remain dry in some cases, but the polymer is able to flow around the tows and the material is rigid and self-supporting. Also the dry fibers at the center of each tow may actually allow freer movement and better energy absorption, although this remains to be seen and may become apparent upon analysis of ballistic results and completion of the data set.

5 Recommendation for Further Work

The production of further small panels would allow repeat testing on conditions investigated to date as well as expanding the scope to higher pressures and longer molding times. It has been shown that quasi-static energy absorption has some dependence on molding parameters and it may be possible to correlate this with ballistic test data.

The use of nano-reinforced polymer films for this type of application may offer synergistic benefits of a 2 phase reinforced matrix material for both static properties as well as ballistic energy absorbance.

High temperature vacuum bagging was one of the fabrication methods under consideration at the outset of the project. This is a potential future production method for this type of panel and the current high cost of the materials involved can be avoided by the cleaver use of high temperature suitable, low cost materials as previously stated.

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Appendix

Panel No.	Material	Reinforcement		Polymer Film		Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm^{-2})	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
		Weight (g m^{-2})	No. Layers	Film Thickness (μm)	No. Layers						
PEE1150c	LDPE/E-glass	210	15	100	16	150	1	0.438	5.56 FSP	3.322	7.588
PEE3150c	LDPE/E-glass	210	15	100	16	150	3	0.447	5.56 FSP	4.138	9.252
PEE5150c	LDPE/E-glass	210	15	100	16	150	5	0.439	5.56 FSP	4.679	10.669
PEE1170c	LDPE/E-glass	210	15	100	16	170	1	0.443	5.56 FSP	3.980	8.976
PEE3170c	LDPE/E-glass	210	15	100	16	170	3	0.439	5.56 FSP	4.523	10.308
PEE5170c	LDPE/E-glass	210	15	100	16	170	5	0.441	5.56 FSP	5.181	11.752
PEE1190c	LDPE/E-glass	210	15	100	16	190	1	0.444	5.56 FSP	4.107	9.248
PEE3190c	LDPE/E-glass	210	15	100	16	190	3	0.445	5.56 FSP	4.798	10.783
PEE5190c	LDPE/E-glass	210	15	100	16	190	5	0.437	5.56 FSP	5.034	11.531
PEE1210c	LDPE/E-glass	210	15	100	16	210	1	0.442	5.56 FSP	4.114	9.313
PEE3210c	LDPE/E-glass	210	15	100	16	210	3	0.441	5.56 FSP	5.321	12.055
PEE5210c	LDPE/E-glass	210	15	100	16	210	5	0.436	5.56 FSP	5.388	12.345

Table A.1 Molding Parameters for LDPE/E-glass Panels

Panel No.	Material	Reinforcement		Polymer Film		Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm^{-2})	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
		Weight (g m^{-2})	No. Layers	Film Thickness (μm)	No. Layers						
PPE1170c	Polypropylene/E-glass	210	15	90	16	170	1	0.424	5.56 FSP	5.053	11.910
PPE3170c	Polypropylene/E-glass	210	15	90	16	170	3	0.425	5.56 FSP	6.110	14.388
PPE5170c	Polypropylene/E-glass	210	15	90	16	170	5	0.420	5.56 FSP	6.691	15.933
PPE1190c	Polypropylene/E-glass	210	15	90	16	190	1	0.424	5.56 FSP	5.236	12.345
PPE3190c	Polypropylene/E-glass	210	15	90	16	190	3	0.422	5.56 FSP	6.529	15.476
PPE5190c	Polypropylene/E-glass	210	15	90	16	190	5	0.422	5.56 FSP	7.577	17.955
PPE1210c	Polypropylene/E-glass	210	15	90	16	210	1	0.423	5.56 FSP	6.524	15.416
PPE3210c	Polypropylene/E-glass	210	15	90	16	210	3	0.422	5.56 FSP	7.823	18.554
PPE5210c	Polypropylene/E-glass	210	15	90	16	210	5	0.420	5.56 FSP	7.758	18.461
PPE1230c	Polypropylene/E-glass	210	15	90	16	230	1	0.424	5.56 FSP	6.514	15.356
PPE3230c	Polypropylene/E-glass	210	15	90	16	230	3	0.419	5.56 FSP	7.869	18.767
PPE5230c	Polypropylene/E-glass	210	15	90	16	230	5	0.414	5.56 FSP	7.664	18.520

Table A.2 Molding Parameters for Polypropylene/E-glass Panels

Panel No.	Material	Reinforcement		Polymer Film		Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm⁻²)	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
		Weight (g m⁻²)	No. Layers	Film Thickness (μm)	No. Layers						
PTE1260c	PET/E-glass	210	15	100	16	260	1	0.496	5.56 FSP	7.610	15.356
PTE3260c	PET/E-glass	210	15	100	16	260	3	0.473	5.56 FSP	7.341	15.534
PTE5260c	PET/E-glass	210	15	100	16	260	5	0.463	5.56 FSP	5.466	11.809
PTE1270c	PET/E-glass	210	15	100	16	270	1	0.485	5.56 FSP	7.570	15.622
PTE3270c	PET/E-glass	210	15	100	16	270	3	0.455	5.56 FSP	6.082	13.366
PTE5270c	PET/E-glass	210	15	100	16	270	5	0.446	5.56 FSP	5.701	12.787
PTE1280c	PET/E-glass	210	15	100	16	280	1	0.478	5.56 FSP	7.171	15.003
PTE3280c	PET/E-glass	210	15	100	16	280	3	0.445	5.56 FSP	6.196	13.935
PTE5280c	PET/E-glass	210	15	100	16	280	5	0.428	5.56 FSP	5.156	12.045
PTE1290c	PET/E-glass	210	15	100	16	290	1	0.468	5.56 FSP	7.428	15.883
PTE3290c	PET/E-glass	210	15	100	16	290	3	0.439	5.56 FSP	5.759	13.132
PTE5290c	PET/E-glass	210	15	100	16	290	5	0.420	5.56 FSP	1.552	3.692

Table A.3 Molding Parameters for PET/E-glass Panels

Panel No.	Material	Reinforcement		Polymer Film		Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm⁻²)	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
		Weight (g m⁻²)	No. Layers	Film Thickness (μm)	No. Layers						
N6E1240c	Nylon6/E-glass	210	15	50	32	240	1	0.472	5.56 FSP	6.597	13.977
N6E3240c	Nylon6/E-glass	210	15	50	32	240	3	0.470	5.56 FSP	7.553	16.072
N6E5240c	Nylon6/E-glass	210	15	50	32	240	5	0.466	5.56 FSP	7.206	15.472
N6E1250c	Nylon6/E-glass	210	15	50	32	250	1	0.465	5.56 FSP	6.960	14.963
N6E3250c	Nylon6/E-glass	210	15	50	32	250	3	0.461	5.56 FSP	7.276	15.778
N6E5250c	Nylon6/E-glass	210	15	50	32	250	5	0.460	5.56 FSP	7.270	15.796
N6E1260c	Nylon6/E-glass	210	15	50	32	260	1	0.472	5.56 FSP	7.104	15.042
N6E3260c	Nylon6/E-glass	210	15	50	32	260	3	0.464	5.56 FSP	7.069	15.224
N6E5260c	Nylon6/E-glass	210	15	50	32	260	5	0.460	5.56 FSP	7.306	15.872
N6E1270c	Nylon6/E-glass	210	15	50	32	270	1	0.468	5.56 FSP	6.954	14.873
N6E3270c	Nylon6/E-glass	210	15	50	32	270	3	0.465	5.56 FSP	8.004	17.216
N6E5270c	Nylon6/E-glass	210	15	50	32	270	5	0.459	5.56 FSP	7.911	17.220

Table A.4 Molding Parameters for Nylon6/E-glass Panels

Panel No.	Material	Reinforcement		Polymer Film		Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm⁻²)	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
		Weight (g m⁻²)	No. Layers	Film Thickness (μm)	No. Layers						
PCE1240c	Polycarbonate/E-glass	210	15	250	16	240	1	0.745	5.56 FSP	15.042	20.178
PCE3240c	Polycarbonate/E-glass	210	15	250	16	240	3	0.722	5.56 FSP	14.974	20.727
PCE5240c	Polycarbonate/E-glass	210	15	250	16	240	5	0.695	5.56 FSP	14.596	21.001
PCE1260c	Polycarbonate/E-glass	210	15	250	16	260	1	0.713	5.56 FSP	15.334	21.495
PCE3260c	Polycarbonate/E-glass	210	15	250	16	260	3	0.658	5.56 FSP	15.891	24.138
PCE5260c	Polycarbonate/E-glass	210	15	250	16	260	5	0.618	5.56 FSP	14.874	24.071
PCE1280c	Polycarbonate/E-glass	210	15	250	16	280	1	0.672	5.56 FSP	16.046	23.874
PCE3280c	Polycarbonate/E-glass	210	15	250	16	280	3	0.594	5.56 FSP	14.063	23.684
PCE5280c	Polycarbonate/E-glass	210	15	250	16	280	5	0.546	5.56 FSP	11.849	21.699
PCE1300c	Polycarbonate/E-glass	210	15	250	16	300	1	0.636	5.56 FSP	14.394	22.637
PCE3300c	Polycarbonate/E-glass	210	15	250	16	300	3	0.524	5.56 FSP	9.825	18.747
PCE5300c	Polycarbonate/E-glass	210	15	250	16	300	5	0.481	5.56 FSP	9.396	19.516

Table A.5 Molding Parameters for Polycarbonate/E-glass Panels

Panel No.	Material	Reinforcement		Polymer Film		Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm⁻²)	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
		Weight (g m⁻²)	No. Layers	Film Thickness (μm)	No. Layers						
PES1150	LDPE/S2-glass	200	15	100	32	150	1	0.575	5.56 FSP	42.103	73.213
PES1170	LDPE/S2-glass	200	15	100	32	170	1	0.577	5.56 FSP	42.399	73.534
PES1190	LDPE/S2-glass	200	15	100	32	190	1	0.551	5.56 FSP	41.855	75.898
PES1210	LDPE/S2-glass	200	15	100	32	210	1	0.550	5.56 FSP	35.860	65.179
PES2150	LDPE/S2-glass	200	15	100	32	150	2	0.585	5.56 FSP	46.790	79.937
PES2170	LDPE/S2-glass	200	15	100	32	170	2	0.573	5.56 FSP	50.073	87.439
PES2190	LDPE/S2-glass	200	15	100	32	190	2	0.554	5.56 FSP	36.646	66.188
PES2210	LDPE/S2-glass	200	15	100	32	210	2	0.548	5.56 FSP	36.555	66.729
PES3150	LDPE/S2-glass	200	15	100	32	150	3	0.578	5.56 FSP	47.666	82.503
PES3170	LDPE/S2-glass	200	15	100	32	170	3	0.589	5.56 FSP	52.738	89.473
PES3190	LDPE/S2-glass	200	15	100	32	190	3	0.549	5.56 FSP	38.136	69.469
PES3210	LDPE/S2-glass	200	15	100	32	210	3	0.543	5.56 FSP	36.342	66.892
PES4150	LDPE/S2-glass	200	15	100	32	150	4	0.566	5.56 FSP	51.028	90.210
PES4170	LDPE/S2-glass	200	15	100	32	170	4	0.538	5.56 FSP	51.554	95.870
PES4190	LDPE/S2-glass	200	15	100	32	190	4	0.536	5.56 FSP	37.652	70.197
PES4210	LDPE/S2-glass	200	15	100	32	210	4	0.537	5.56 FSP	36.087	67.258
PES5150	LDPE/S2-glass	200	15	100	32	150	5	0.563	5.56 FSP	53.503	95.036
PES5170	LDPE/S2-glass	200	15	100	32	170	5	0.539	5.56 FSP	50.986	94.519
PES5190	LDPE/S2-glass	200	15	100	32	190	5	0.533	5.56 FSP	38.138	71.594
PES5210	LDPE/S2-glass	200	15	100	32	210	5	0.535	5.56 FSP	37.086	69.351

Table A.6 Molding Parameters for LDPE/S2-glass Panels

Panel No.	Material	Reinforcement Weight (g m^{-2})	No. Layers	Polymer Film Film Thickness (μm)	No. Layers	Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm^{-2})	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
PPS1170	Polypropylene/S2-glass	200	15	90	32	170	1	0.544	5.56 FSP	34.565	63.552
PPS1190	Polypropylene/S2-glass	200	15	90	32	190	1	0.531	5.56 FSP	33.397	62.928
PPS1210	Polypropylene/S2-glass	200	15	90	32	210	1	0.526	5.56 FSP	35.575	67.659
PPS1230	Polypropylene/S2-glass	200	15	90	32	230	1	0.511	5.56 FSP	33.900	66.301
PPS2170	Polypropylene/S2-glass	200	15	90	32	170	2	0.531	5.56 FSP	34.665	65.268
PPS2190	Polypropylene/S2-glass	200	15	90	32	190	2	0.520	5.56 FSP	35.567	68.351
PPS2210	Polypropylene/S2-glass	200	15	90	32	210	2	0.524	5.56 FSP	37.236	71.037
PPS2230	Polypropylene/S2-glass	200	15	90	32	230	2	0.503	5.56 FSP	34.441	68.535
PPS3170	Polypropylene/S2-glass	200	15	90	32	170	3	0.531	5.56 FSP	36.612	68.938
PPS3190	Polypropylene/S2-glass	200	15	90	32	190	3	0.502	5.56 FSP	34.416	68.563
PPS3210	Polypropylene/S2-glass	200	15	90	32	210	3	0.511	5.56 FSP	36.098	70.577
PPS3230	Polypropylene/S2-glass	200	15	90	32	230	3	0.500	5.56 FSP	34.035	68.014
PPS4170	Polypropylene/S2-glass	200	15	90	32	170	4	0.530	5.56 FSP	33.993	64.139
PPS4190	Polypropylene/S2-glass	200	15	90	32	190	4	0.520	5.56 FSP	34.491	66.365
PPS4210	Polypropylene/S2-glass	200	15	90	32	210	4	0.504	5.56 FSP	36.727	72.873
PPS4230	Polypropylene/S2-glass	200	15	90	32	230	4	0.466	5.56 FSP	32.437	69.680
PPS5170	Polypropylene/S2-glass	200	15	90	32	170	5	0.525	5.56 FSP	34.548	65.766
PPS5190	Polypropylene/S2-glass	200	15	90	32	190	5	0.506	5.56 FSP	34.736	68.637
PPS5210	Polypropylene/S2-glass	200	15	90	32	210	5	0.485	5.56 FSP	34.840	71.808
PPS5230	Polypropylene/S2-glass	200	15	90	32	230	5	0.498	5.56 FSP	35.564	71.450

Table A.7 Molding Parameters for Polypropylene/S2-glass Panels

Panel No.	Material	Reinforcement Weight (g m^{-2})	No. Layers	Polymer Film Film Thickness (μm)	No. Layers	Processing Temperature (°C)	Compression Time (mins)	Areal Density (g cm^{-2})	Penetrator	Energy Absorbed (J)	Normalised Energy Absorbance (J/unit areal density)
HEXEGN6	E-glass/Nylon6	521	9	-	-	274	10	0.631	5.56 FSP	14.900	23.621
HEXS2PEI	S2-glass/PEI	418	10	-	-	357	10	0.610	5.56 FSP	17.099	28.043
HEXS2PEEK	S2-glass/PEEK	418	10	-	-	385	10	0.579	5.56 FSP	17.362	29.981

Table A.8 Molding Parameters for Pre-impregnated Towflex® Panels